High-Frequency Measurement of Ultrasound Using Flexural Ultrasonic Transducers

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Abstract—**Flexural ultrasonic transducers are a widely available type of ultrasonic sensor used for flow measurement, proximity, and industrial metrology applications. The flexural ultrasonic transducer is commonly operated in one of the axisymmetric modes of vibration in the low-kilohertz range, under 50 kHz, but there is an increasing demand for higher frequency operation, towards 300 kHz. At present, there are no reports of the measurement of high-frequency vibrations using flexural ultrasonic transducers. This research reports on the measurement of high-frequency vibration in flexural ultrasonic transducers, utilizing electrical impedance and phase measurement, laser Doppler vibrometry, and response spectrum analysis through the adoption of two flexural ultrasonic transducers in a transmit–receive configuration. The outcomes of this research demonstrate the ability of flexural ultrasonic transducers to measure high-frequency ultrasound in air, vital for industrial metrology.**

Index Terms—**Acoustic transducers, frequency measurement, ultrasonic sensors, air-coupled ultrasound.**

I. Introduction

The accurate detection of high frequency vibrations in industrial flow and measurement ultrasound systems is essential, especially at relatively low power with high efficiency. There are a range of measurement technologies currently available for air-coupled ultrasonic measurement that use different physical techniques for the generation and detection of ultrasound in gas. For example, through-thickness or radial modes of piezoelectric transducer vibrations have been used in many commercial transducers [1], often using matching layers to improve coupling efficiency into gas because of the high acoustic impedance mismatch between the piezoelectric material and the gas [2]. These sensors are capable of operating up to frequencies of 5 MHz, but generally require high voltages, in the region of 20 V or higher, and have at least part of their radiating face made from a polymer or other non-robust material. MEMS-type fabrication approaches have been used to manufacture CMUT [3] and PMUT [4] type sensors, both of which can be small, robust devices that can require high voltages to drive them, and in the case of a CMUT a large biasing voltage. These MEMS-type devices are capable of generating or detecting ultrasonic waves in gas up to MHz frequencies.

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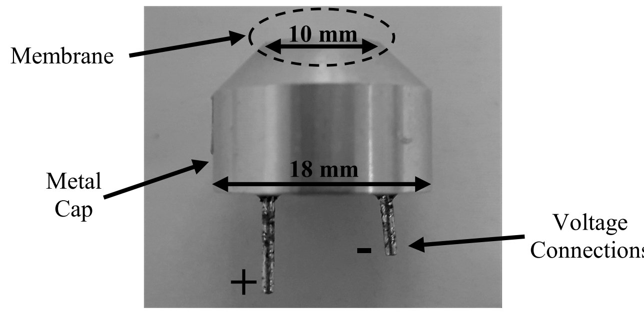

Fig. 1. The flexural ultrasonic transducer, typical of the device investigated in this study.

There is a growing interest to be able to measure high frequency ultrasound waves in air. For example, in flow measurement, high frequency ultrasound is often desirable to reduce the interference of the system noise with a centre frequency of several dozens of kHz, originating from components inside flow structures such as valves. Improvements to measurement resolution are also possible with higher frequency operation, and reduced signal diffraction. Currently, in non-destructive testing and evaluation applications, ultrasound devices can include matching layers to generate and detect high frequency ultrasound, normally with high input voltage. These devices rely on through-thickness or radial resonant modes of a piezoelectric element in order to generate ultrasonic vibrations.

A primary candidate for high frequency transmission and detection of ultrasound is the flexural ultrasonic transducer, which is an ultrasound sensor that has already been applied in proximity measurement, for example car parking systems, flow measurement, and industrial metrology processes [2], [5]. The flexural ultrasonic transducer is composed of a driving element such as a piezoelectric ceramic, bonded to a metallic membrane, formed as part of the transducer cap. An example of a flexural ultrasonic transducer is shown in Fig. 1, representative of the configuration used in this study.

Flexural ultrasonic transducers currently tend to be operated up to approximately 50 kHz in industrial applications, where the resonance frequencies of its vibration modes are dependent on the cap material and geometry. This research demonstrates how flexural ultrasonic transducers offer an alternative solution to provide high efficiency ultrasound transmission and reception in air, at high ultrasonic frequencies.

The measurement of high frequency ultrasound in air has been reported [6], but was limited to relatively large,

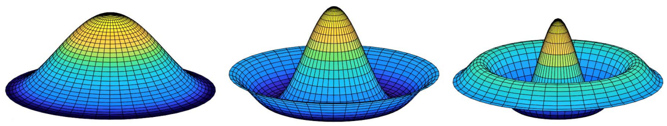

Fig. 2. The first three axisymmetric vibration modes of a flexural ultrasonic transducer.

high-power transducers, with operating frequency up to around 100 kHz, and measurement was restricted to using acoustic microphone and interferometry techniques. All of the alternative air-coupled sensors and other micro-machined designs specified thus far operate on a different physical principle to the extremely robust, low cost, low voltage, high efficiency flexural cap type sensors described in this study, and these alternative transducers have different advantages and disadvantages for various applications that are beyond the scope of this paper to examine in detail.

The flexural ultrasonic transducer has been shown to vibrate according to the dynamic modes of an edge-clamped plate [7], [8], where the cap membrane is modelled as the mechanical equivalence of the plate. The operating modes of a flexural ultrasonic transducer are usually the fundamental axisymmetric modes, given the nomenclature of (0,0), (1,0), and (2,0) in this research [7], [9]. These are directly related to the dynamic plate modes, the resonance frequencies for which are dependent on the plate, or cap membrane, material and geometrical dimensions of diameter and thickness. Through the control of the physical properties of the membrane, the vibration of which dominates the dynamic response of a flexural ultrasonic transducer, the resonance frequencies of the fundamental modes of vibration can be defined. These physical properties are principally the geometrical dimensions and the elastic modulus of the material, where a smaller membrane diameter or thicker membrane increases the resonance frequencies, and a lower elastic modulus decreases the resonance frequencies. The three fundamental axisymmetric mode shapes are shown in Fig. 2, which have been computed using the mathematical software MATLAB (MathWorks), and are representative of the deformation of the cap membrane of a flexural ultrasonic transducer, highlighted through the dashed ellipse in Fig 1.

The modelling and simulation of the vibration response of a flexural ultrasonic transducer has been reported in detail [10]. The full derivation for simulating the rise to steady-state, and the resonant decay, for a transducer excited by a burst sinusoidal signal was demonstrated, showing a close correlation with experimental measurements. Burst signals are commonly used to drive flexural ultrasonic transducers, and so consideration of the vibration response of the transducer prior to steady-state was essential. Finite element methods can also be used to model the transducer, for example PZFlex® finite element analysis software, which is especially useful for the optimisation of transducer output and efficiency.

In this research, a new experimental setup is configured to enable the transmission and detection of high frequency ultrasound waves in air, above 50 kHz and into the hundreds of kHz, for the three fundamental axisymmetric modes of vibration. The transducer shown in Fig. 1 was selected based on its resonance frequencies at the (1,0) and (2,0) modes, both of which were measured to be above 100 kHz. Three fundamental axisymmetric vibration modes are investigated in this research, because this is an expedient method of raising the operational frequency of the flexural ultrasonic transducer, without experiencing problems associated with transducer fabrication. The resonance frequency of the (0,0) mode can in theory be significantly increased, but this relies on a stiffer cap membrane, produced by either increasing the magnitude of the elastic properties of the material, such as Young's modulus, or dimensional changes to the cap membrane. For example, a reduction in diameter and an increase in membrane thickness will increase the resonance frequencies of the transducer. However, this causes severe restriction in the ability to fabricate a transducer with precision, and also limits the effectiveness of the piezoelectric ceramic to impart the energy required to generate the bending modes in the cap membrane. It is for these reasons that measurement of three axisymmetric vibration modes in air has been conducted.

Measurement of the amplitude-time responses of a flexural ultrasonic transducer can be undertaken through different techniques including laser Doppler vibrometry (LDV) or with an acoustic microphone. However, a laser Doppler vibrometer only measures the vibration of the membrane, and is not perfectly representative of measurements of the ultrasound wave in the far-field, or those which would be made in an industrial environment. An acoustic microphone is capable of detecting far-field vibration, but instruments such as the Brüel & Kjær BK 4138-A-015, which has been used in previous studies [11], are often calibrated for frequencies below those of the (1,0) and (2,0) modes presented in this study. Therefore an alternative approach to accurately measure high frequency ultrasound waves is required. The experimental setup utilized in this research incorporates two flexural ultrasonic transducers configured in a transmit-receive mode of operation, with signal amplification where necessary, to ensure signal acquisition with high SNR. It is demonstrated how high frequency ultrasound measurements can be made using flexural ultrasonic transducers, by configuring the two transducers in a transmit-receive mode of operation. By altering the measurement angle, the change in the amplitude response of the ultrasound wave can be mapped to produce an amplitude spectrum for a given drive frequency, termed an ultrasonic response profile. This ultrasonic response profile provides an indication of the mode of vibration at which the transducer is being operated.

This research forms the foundation for the analysis of high frequency flexural ultrasonic transducers (HiFFUTs), which are a new class of ultrasound transducer. The HiFFUT concept is an evolution of the classical flexural ultrasonic transducer. The understanding of the physics of the flexural ultrasonic transducer at high frequencies, as reported in this study, is essential to the design and development of HiFFUTs.

II. METHODOLOGY

Commercial flexural ultrasonic transducers (Multicomp) were procured for analysis. These transducers are widely available, and are designed for either transmitting or receiving ultrasound. They are composed of an aluminium cap, as shown in Fig. 1, with a circular membrane layer. A piezoelectric ceramic is bonded to the underside of this membrane with an adhesive such as epoxy resin, and an air-silicone backing provides the transducer with the required damping. To enable the measurement and analysis of high frequency ultrasound transmitted by a flexural ultrasonic transducer, a range of experimental techniques were employed.

A. Characterization of Vibration Modes

The mode shapes of the axisymmetric modes, the resonance frequencies of which were measured using electrical impedance analysis, can be determined using different techniques, such as a laser Doppler vibrometer, or an acoustic microphone, such as that manufactured for high frequency measurement (Brüel & Kjær Sound & Vibration Measurement A/S instrument BK 4138-A-015). However, the acoustic microphone was not incorporated into the measurement setup since it is rated for use up to 140 kHz, which is a lower frequency than those of the (1,0) and (2,0) modes in this study.

An impedance gain/phase analyser (Agilent 4294A) was used to measure the resonance frequencies of the transmitter flexural ultrasonic transducer, determined from both electrical impedance and phase, which were obtained as functions of frequency. The vibration modes of the transmitter flexural ultrasonic transducer were then characterized using LDV (Polytec OFV-5000) to provide a confirmation of the modes of vibration at those frequencies. This was undertaken to exhibit the first three fundamental vibration modes representing the axisymmetric modes.

LDV provides an accurate measure of the vibration modes of the membrane, but it is of interest to be able to characterize the far-field ultrasonic response profile, for consideration of practical application. For this purpose, a novel experimental setup was utilized, incorporating a second flexural ultrasonic transducer as a receiver. Ultrasound waves at high frequencies tend to rapidly attenuate in air in comparison to low frequency waves, thereby decreasing the signal-to-noise ratio (SNR) of the received signal, and hence lowering the measurement accuracy. A signal amplifier (Sonemat Two Channel Echo) was therefore integrated into this setup to ensure the detection of ultrasound at all frequency levels, including high frequencies above 100 kHz. The complete experimental setup is shown in Fig. 3.

The two flexural ultrasonic transducers are configured in a transmit-receive mode, where a drive signal is applied to the flexural ultrasonic transducer operating as a transmitter. The ultrasonic wave propagated by the transmitter is subsequently detected by the flexural ultrasonic transducer designated as the receiver. The measured ultrasound response is then directed to the measurement oscilloscope, where signal averaging is applied to ensure a clear response is displayed.

A continuous-wave sinusoidal drive signal with a nominal drive voltage of 10 $V_{P\text{-}P}$ was applied to the transmitter flexural ultrasonic transducer at the resonance frequency of interest. The voltage amplitude of the vibration response was then measured using the receiver flexural ultrasonic transducer, situated at a distance of 500 mm from the transmitter flexural ultrasonic transducer. This was conducted for a range of angles, by rotating the transmitter flexural ultrasonic transducer in 2° increments, as illustrated in Fig. 3. The complete ultrasonic response profile from the transmitter flexural ultrasonic transducer was then constructed using this information, for the (0,0) and (1,0) modes of vibration only. This is because of a low SNR for the (2,0) mode. These far-field ultrasonic response profiles were then correlated with the mode shapes shown in Fig. 2, to confirm that the measured mode of vibration is correctly attributed to the resonance frequency measured using electrical impedance analysis. It should be noted that the measured ultrasonic response profiles are representative of a combination of the radiation patterns from the two flexural ultrasonic transducers. A radiation pattern is generated from the transmitter, which combines with the vibration response of the receiver, which is directly caused by the transmitted ultrasonic wave.

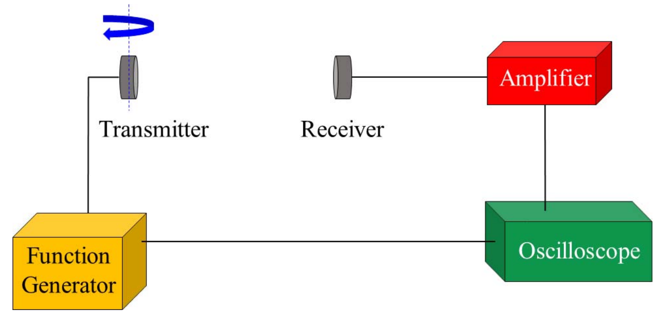

Fig. 3. The experimental setup to measure the ultrasonic response profiles and amplitude-time spectra of the flexural ultrasonic transducer operated as a transmitter, through the use of a second transducer as a receiver.

B. Response Spectrum Analysis

The mode shape results were used in conjunction with the electrical impedance measurements in order to define the drive parameters for the transmitter flexural ultrasonic transducer in each of the three axisymmetric modes of vibration. This enabled an amplitude-time spectrum at resonance to be generated for each mode of vibration. In all cases, a burst sinusoidal drive signal of 10 $V_{P\text{-}P}$ and 150 cycles was applied to the transmitter flexural ultrasonic transducer, with signal gain applied to the receiver flexural ultrasonic transducer where necessary to ensure suitable measurement SNR. The amplitude-time spectrum for each mode of vibration was measured by the receiver flexural ultrasonic transducer, positioned at a distance of 500 mm in separation, with cap membranes of the two transducers diametrically opposing, and fast Fourier transforms (FFTs) of the signals were subsequently calculated, to provide the response measurement in the frequency domain. The resonance frequencies identified using each technique were then compared.

III. Experimental Results

The geometrical approximation for the behaviour of the flexural ultrasonic transducer cap membrane has previously

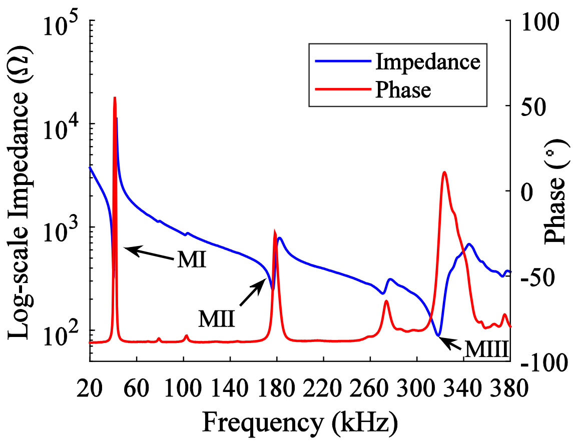

Fig. 4. Electrical analysis of the flexural ultrasonic transducer operated as a transmitter, showing the electrical impedance and phase as functions of frequency.

been considered as an edge-clamped plate [7], [9], and estimations of the vibration modes can be produced using Bessel functions, which have been detailed in the literature and are not repeated here [7]. With the Bessel functions applied to an aluminium edge-clamped plate of 10 mm diameter and 0.40 mm plate thickness, the frequencies of the (0,0), (1,0), and (2,0) modes were calculated to be 40.22 kHz, 156.56 kHz, and 350.77 kHz respectively. These calculated frequencies are estimations, since the precise membrane thickness of each transducer was not available. The frequencies are very sensitive to the geometrical dimensions, where sub-millimeter deviations in magnitude produce significant changes in calculated frequency. Furthermore, the cap membrane is modelled as an edge-clamped plate, which will not precisely represent the dynamics of the flexural ultrasonic transducer in practical application.

The impedance-frequency and phase-frequency spectra of the flexural ultrasonic transducer operating as a transmitter are shown in Fig. 4, for a measurement frequency range of 20 kHz to 380 kHz, the frequency range in which the (0,0), (1,0), and (2,0) modes of vibration were predicted to exist. The resonance frequencies of the flexural ultrasonic transducer are obtained by the identification of the frequency with the minimum impedance at each mode. Through electrical impedance analysis, these frequencies have been identified as those of individual modes of vibration, as MI at 40.25 kHz, MII at 176.60 kHz, and MIII at 318.35 kHz, in the designated frequency range.

There are smaller discontinuities in the spectra which have been measured, in particular around 80 kHz, 100 kHz, and 270 kHz. The energy associated with these other modes is very low compared to the energy of MI, MII and MIII. However, it is possible to acquire an estimation of the characteristics of these modes, through the mathematics of the Bessel functions. For an assumed membrane diameter and thickness used to predict the resonance frequencies of the axisymmetric modes, the application of the Bessel functions provides estimations of asymmetric modes. The (0,1) mode of vibration is predicted at a resonance frequency of 83.69 kHz, (0,2) at 137.3 kHz, and the (1,1) mode at 239.46 kHz. These results provide an indication of the vibration modes of the transducer at these frequencies.

It is not possible to determine the mode shapes associated with measured resonance frequencies using electrical impedance analysis alone. However, the flexural ultrasonic transducer is a coupled electromechanical system, and so the identification of the resonance frequencies of the vibration modes using the electrical impedance technique is suitable for establishing the drive frequencies used for mode shape measurement.

The modes of vibration of the transmitter flexural ultrasonic transducer were first measured using the LDV method, and secondly in the far-field through the integration of a receiver flexural ultrasonic transducer, nominally identical to the transmitter, into the experimental setup as shown in Fig. 3. For the LDV measurement, a nominal 20 V_{P-P} sinusoidal excitation signal was applied to the transmitter flexural ultrasonic transducer, with 16 signal averages. The results of the LDV measurement process are shown in Fig. 5.

The frequencies of maximum output voltage, representing maximum output amplitude and hence resonance, provide a measure of resonance frequency. This was performed at the centre of the flexural ultrasonic transducer cap membrane, and the resonance frequencies were measured to be 40.5 kHz for the (0,0) mode, 177.4 kHz for the (1,0) mode, and 318.7 kHz for the (2,0) mode. A nominal 20 V_{P-P} drive voltage has been reported in this study, but the drive voltage exhibited a reduction in each case, due to the variation of impedance of the transducer as the frequency was increased. The drive voltage for the (0,0) mode was 19.06 V_{P-P}, 17.94 V_{P-P} for the (1,0) mode, and 13.47 V_{P-P} for the (2,0) mode. Signal processing was also applied in the form of 16 averages to ensure measurement signal stability.

The resonance frequencies measured using the LDV technique are close to those measured using electrical impedance analysis, but it should be noted that the minor variation in the frequency magnitude for both modes is expected, due to the difference in clamping conditions required by the different techniques. For the LDV measurement, the flexural ultrasonic transducer had to be supported in a rig to ensure stable measurement of the membrane surface vibration.

The measurement of the transmitter flexural ultrasonic transducer vibration has been demonstrated using an optical technique in the form of LDV. Far-field vibration measurement in air would normally be undertaken using instrumentation such as an acoustic microphone, but since the magnitude of the resonance frequencies of the modes of interest exceed the calibrated measurement range, a secondary flexural ultrasonic transducer has been incorporated into the measurement setup, as shown in Fig. 3. The ultrasonic response profile from the transmitter flexural ultrasonic transducer was measured by this receiver flexural ultrasonic transducer. The ultrasonic response profile measurements allow a representation of the ultrasound wave in the far-field to be produced, providing an indication of the mode shape of the flexural ultrasonic transducer cap membrane for a particular drive frequency. The ultrasonic response profiles for the (0,0) and (1,0) modes of vibration

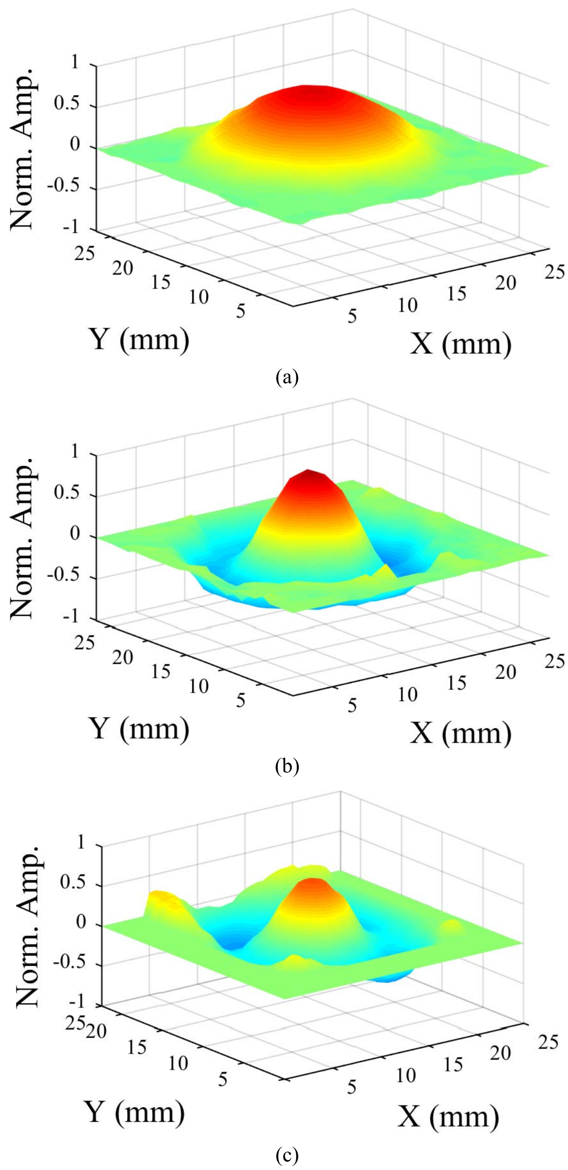

Fig. 5. Axisymmetric vibration modes of the transmitter flexural ultrasonic transducer, showing (a) the (0,0) mode at 40.5 kHz, (b) the (1,0) mode at 177.4 kHz, and (c) the (2,0) mode at 318.7 kHz, measured using LDV. Note, the measurement area of the transducer was reduced in order to capture the (2,0) mode, and the axis numbers of sub-figure (c) have been altered. The slight peaks at the edges of the (2,0) measurement in (c) are the consequence of a reduced field of view, with measurement taken at the membrane edge.

are not pure radiation patterns of the transmitted ultrasound wave, since the dynamics of the receiver flexural ultrasonic transducer influence the measured response signal. The signals measured using the experimental setup shown in Fig. 3 are a combination of the emitted waves from the transmitter and receiver flexural ultrasonic transducers, dominated by the transmitter flexural ultrasonic transducer response as a consequence of the comparably high energy level supplied to the device. This is a novel method of measuring high frequency ultrasound in an air environment, with two air-coupled flexural ultrasonic transducers.

The ultrasonic response profile measurement technique was only able to capture low SNR data for the (2,0) mode of vibration around 318 kHz, where the response spectrum was dominated by measurement noise. For this reason, only the ultrasonic response profile measurements of the (0,0) and (1,0) modes of vibration have been reported. In each case, the drive frequency was modulated until the output voltage amplitude reached a maximum, thus providing a reliable measure of the resonance frequency. A similar technique has been used in prior studies with burst sinusoidal signals, where a maximum vibration amplitude around an estimated resonance frequency at steady-state can be used to accurately measure that particular resonance frequency [12]. The burst sinusoidal signal method has an additional advantage, since the over-shoot in the amplitude-time response spectrum indicates a disparity between the drive frequency and the resonance frequency of the flexural ultrasonic transducer [12]. The ultrasonic response profiles for the (0,0) and (1,0) modes were both measured at a distance of 500 mm in air, and the results are shown in Fig. 6.

The required amplifier gain for this transducer type is in the order of 13.6 for the (0,0) mode, and 20.8 for the (1,0) mode, to generate sufficient measurement SNR. The data were recorded with 64 signal averages in each case. The SNR for a burst sinusoidal signal with no averaging applied was determined to be 17.05 dB for the (0,0) mode, and 4.99 dB for the (1,0) mode. These values were both obtained by calculating the root mean square (RMS) of the peak-to-peak voltage measurements (V_{RMS}), before dividing the V_{RMS} of the signal at steady-state by the V_{RMS} of the noise in the response spectrum, after which Eq. (1) was used to find the SNR in terms of dB.

$$\mathrm{SNR} = 20\log_{(10)}\frac{V_{\mathrm{RMS,Signal}}}{V_{\mathrm{RMS,Noise}}} \tag{1}$$

The ultrasonic response profiles displayed in Fig. 6, which are provided with trend-lines for clarity that are not measured data, show the measurement of the resonance frequency of the (0,0) mode to be 39.90 kHz, and 176.20 kHz for the (1,0) mode of vibration, in close correlation with those provided from the measurements shown in Fig. 4 and Fig. 5. The flexural ultrasonic transducers used in this study both possess a rated beam angle of 80° for the (0,0) mode. This means that the half-maximum amplitude is measurable over an 80° span. The result shown in Fig. 6(a) is consistent with this rating.

Based on the differences in measurement instrumentation and boundary conditions, the resonance frequencies do not precisely match those obtained using electrical impedance analysis and LDV. One further reason is the difference in drive voltage applied to the transmitter flexural ultrasonic transducer in each technique, since resonance frequency is dependent on vibration amplitude, due to dynamic nonlinearity [13]. However, the mode shapes of the transmitter flexural ultrasonic transducer can be identified, and correlated with those shown in Fig. 2. In particular, the (1,0) mode shape shown in Fig. 6(b) is evident, where there are clearly observable mode shape nodes. The ultrasonic response profile measured for the (1,0) mode also closely conforms to the rated beam angle of 80°.

The ultrasonic response profile of the (0,0) mode shown in Fig. 6(a) exhibits a sharp peak emitted from the centre of the cap membrane. The interaction between the signals

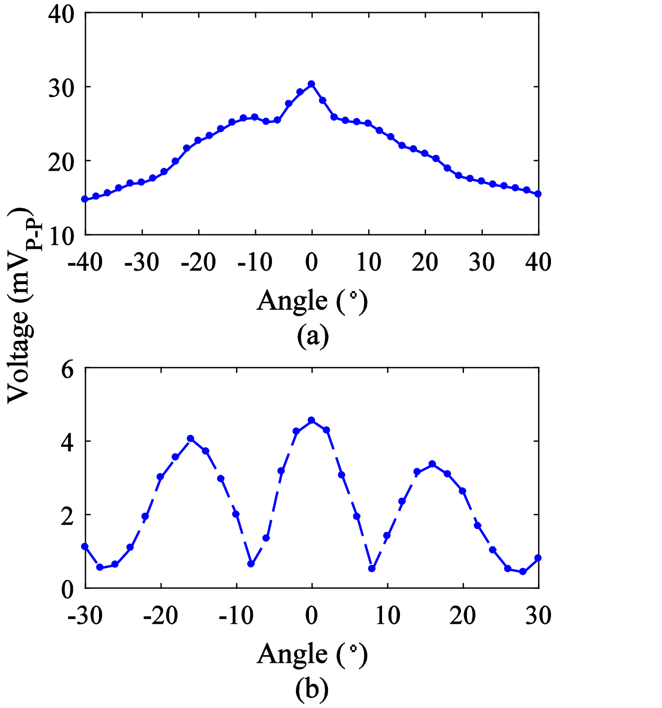

Fig. 6. Ultrasonic response profile measurements of the flexural ultrasonic transducer operated as a transmitter using the flexural ultrasonic transducer operated as a receiver, for (a) the (0,0) mode at 39.90 kHz, and (b) the (1,0) mode at 176.20 kHz. Note the difference in axis scales between the sub-figures, to allow clarity.

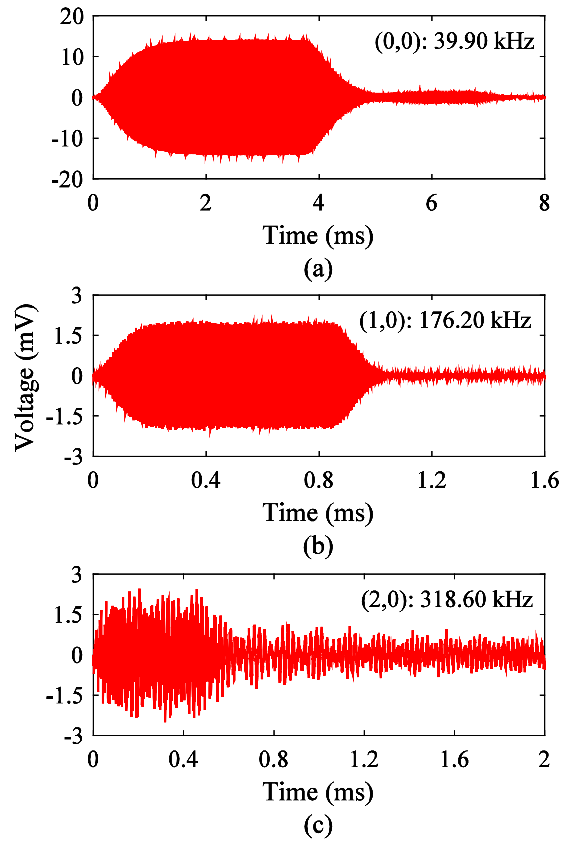

Fig. 7. Amplitude-time spectra of the flexural ultrasonic transducer, for (a) the (0,0), (b) the (1,0), and (c) the (2,0) modes of vibration, measured at a distance of 500 mm. The spectra have been time-shifted for clarity.

from the transmitter and the receiver together produces this response, and this is supported by the results of [14] and [15]. The ultrasonic response profile shape in Fig. 6(a) is caused by a combination of the waves from both flexural ultrasonic transducers, comprising the ultrasound wave of the (0,0) mode from the transmitter, and the vibration response of the receiver. This phenomenon has been demonstrated previously through simulation [15]. In general, the mode shapes measured using LDV and the ultrasonic response profiles have been shown to closely correlate with the mode shapes presented in Fig. 2, confirming that the frequencies of MI and MII from the electrical impedance analysis results shown in Fig. 4 are associated with the (0,0) and (1,0) modes respectively. To investigate the response signals in more detail, the amplitude-time spectra at the resonance frequencies of the (0,0) and (1,0) modes of vibration were obtained using burst sinusoidal signals, and are displayed in Fig. 7. The amplitude-time spectrum of the (2,0) mode is also presented, where relatively high noise is evident, compared to the measured responses for the (0,0) and (1,0) modes.

The results shown in Fig. 7 demonstrate the capability of a flexural ultrasonic transducer to detect high frequency signals in air transmitted from a source flexural ultrasonic transducer with clarity, using a burst sinusoidal signal. The absence of over-shoot in the amplitude responses for the (0,0) and (1,0) modes as the responses transition to steady-state is an indicator of the transducer being driven at its resonance frequencies [12]. This was more difficult to inspect for the response of the (2,0) mode based on the response signal noise, but the drive frequency was defined from that which generated the highest output amplitude.

The voltage magnitudes shown in the results are dependent on the gain which had to be applied in order to obtain a clear representation of the amplitude-time spectrum in each case, and with sufficient SNR. The gains necessary to be applied to generate the (0,0) and (1,0) mode response spectra shown in Fig. 7 are in the region of 13.6 and 20.8 respectively, and approximately 88.3 for the (2,0) mode, for this transducer type. Signal averaging of 64 was used in each case. The results demonstrate that with suitable signal amplification, the high frequency ultrasound vibration of a flexural ultrasonic transducer can be reliably measured in air, with little difference in signal quality between the (0,0) mode at 39.90 kHz and the (1,0) mode at 176.20 kHz. The limits of the measurement setup are demonstrated by the lower signal amplitude and SNR of the amplitude-time spectrum of the (2,0) mode, at 318.60 kHz. However, the response was achieved using a relatively low drive voltage, and with improvements to the measurement setup including signal filtering and adjustments to the transmit-receive configuration, there is opportunity for higher SNR measurements to be captured in air.

An important factor to consider in the comparison between the resonance frequencies determined through electrical impedance measurement or LDV, and the resonance frequencies calculated through FFT processing of the amplitude-time

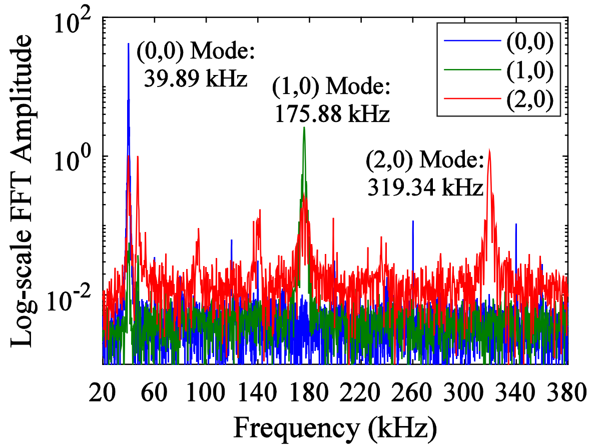

Fig. 8. FFTs of the amplitude-time spectra for the (0,0), (1,0) and (2,0) vibration modes of the transmitter flexural ultrasonic transducer.

spectra, is that measurement with two flexural ultrasonic transducers arranged in a transmit-receive mode is conducted in the far-field, whereas the electrical characterization represents a coupled electromechanical resonance, and the LDV method optically measures the vibration of the flexural ultrasonic transducer cap membrane surface. The amplitude-time spectra shown in Fig. 7 were analyzed in more detail through application of the FFT to the signals. The purpose of this process was to evaluate the frequency content of the signals, and provide indication of the quality of the measured signals. The FFTs of the signals shown in Fig. 7 are exhibited in Fig. 8.

The results of the FFT computation demonstrate the frequency content of each signal, and show the dominant mode in each case. The FFT spectra for the (0,0), (1,0), and (2,0) modes of vibration show the dominant resonance frequencies in each condition to represent those expected for each mode.

This study has provided an experimental configuration and rigorous analysis process for the transmission and detection of high frequency ultrasound using flexural ultrasonic transducers in air. Mathematical prediction, electrical impedance analysis and laser Doppler vibrometry have been used to support the measurement of the vibration modes where possible, through identification of the resonance frequencies of the transducer. The principles underpinning this study can be used to investigate the performance of flexural ultrasonic transducers and other ultrasonic sensors in different environments, including gas and liquid. It is anticipated that this research will provide a platform for further high frequency ultrasound measurement systems to be developed.

IV. Conclusion

Typical working frequencies for commercial flexural ultrasonic transducers are below 50 kHz. This research has demonstrated, through experimental techniques, the capability of flexural ultrasonic transducers for both transmission and detection of high frequency ultrasound in air, for higher order resonant modes. Two flexural ultrasonic transducers were configured in a transmit-receive mode, where ultrasound waves were transmitted and measured up to a frequency of 318 kHz. This research is a key step in the future development of high frequency flexural ultrasonic transducers for operation above 100 kHz.

Acknowledgment

The data from the reported results can be accessed at http://www2.warwick.ac.uk/fac/sci/physics/research/ultra/research/HF1.zip.

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Lei Kang, photograph and biography not available at the time of publication.

Steve Dixon, photograph and biography not available at the time of publication.